Renewable and Sustainable Energy Reviews 29 (2014) 135–150

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Hybrid electric vehicles and their challenges: A review

M.A. Hannan [a,*], F.A. Azidin [a,b], A. Mohamed [a]

[a] Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[b] Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76109, Durian Tunggal, Melaka, Malaysia

ARTICLE INFO

Article history:
Received 23 August 2012
Accepted 26 August 2013
Available online 17 September 2013

Keywords:
Fuel cell
Battery
Super capacitors
Energy management system
Hybrid electric vehicle

ABSTRACT

There are numbers of alternative energy resources being studied for hybrid vehicles as preparation to replace the exhausted supply of petroleum worldwide. The use of fossil fuel in the vehicles is a rising concern due to its harmful environmental effects. Among other sources battery, fuel cell (FC), super capacitors (SC) and photovoltaic cell i.e. solar are studied for vehicle application. Combinations of these sources of renewable energies can be applied for hybrid electric vehicle (HEV) for next generation of transportation. Various aspects and techniques of HEV from energy management system (EMS), power conditioning and propulsion system are explored in this paper. Other related fields of HEV such as DC machine and vehicle system are also included. Various type models and algorithms derived from simulation and experiment are explained in details. The performances of the various combination of HEV system are summarized in the table along with relevant references. This paper provides comprehensive survey of hybrid electric vehicle on their source combination, models, energy management system (EMS) etc. developed by various researchers. From the rigorous review, it is observed that the existing technologies more or less can capable to perform HEV well; however, the reliability and the intelligent systems are still not up to the mark. Accordingly, this review have been lighted many factors, challenges and problems sustainable next generation hybrid vehicle.

Contents

* Corresponding authors. Tel.: +60 3 8921 7014.
E-mail address: hannan@eng.ukm.my (M.A. Hannan).

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.08.097

1. Introduction

An emphasis on green technology is greatly demanded of modern cities. The significant growth of today's cities has led to an increased use of transportation, resulting in increased pollution and other serious environmental problems. Gases produced by vehicle should be controlled and proactive measures should be taken to minimize these emissions. The automotive industry has introduced hybrid cars, such as the Honda Insight and the Toyota Prius that minimize the use of combustion engines by integrating them with electric motors [1]. Such technology has a positive effect on the environment by reducing gas emission. The greatest challenge in research activities today is developing near zero-emission powered vehicles. Electric vehicles powered by renewable energies offer a possible solution because they only emit natural byproducts and not exhaust fumes, which improve the air quality in cities and, thus the health of their populations [2].

One potential renewable energy device to power vehicles is the FC. A FC is an electrochemical device that produces DC electrical energy through a chemical reaction [3]. It consists of an anode, an anode catalyst layer, an electrolyte, a cathode and a cathode catalyst layer. Multiple FCs are arranged in series or parallel in a stack to produce the desired voltage and current [4]. FCs can be used for transportation applications from scooters to tramways, for combined heat and power (CHP) systems and in portable power supplies. In fact, the applications of FCs start at the small scale requiring 200 W and can reach the level of small power plants requiring 500 kW [5–7]. FC technology uses hydrogen as the main source of energy that produces the electricity needed to drive an electric vehicle. In comparison to an internal combustion engine (ICE) that emits gases such as NO_x and CO_2, FC emits water as byproduct [8,9]. However, the downside to FCs is their slow dynamic properties, and therefore, they require auxiliary sources, such as batteries and SCs [10]. Batteries, which have high power density but low energy density have problem in longer charging time which can take from 1 h to several hours for full charge. On the positive side, batteries supply voltage more consistently than FCs. Batteries that are typically used with FCs, which are lead–acid, Li-ion and Ni–MH batteries [11]. In the energy management system for hybrid vehicles, batteries can be charged during regenerative braking and from the residual energy of FCs in low and no load power systems. In this case, batteries are implemented for energy storage and can supply energy continuously depending on the charge and discharge time cycle. Unfortunately, batteries have a limited life cycle that depends on the operating temperature (approximately 20 °C) and on the depth of discharge and the number of discharge cycles. Typically, lead-acid batteries can sustain1000 cycles while Li-ion batteries are limited to 2000 cycles [11]. In addition, Li-ion and Ni–MH batteries have a higher energy density and are lighter compared with lead–acid batteries. However, lead–acid batteries have an advantage over other batteries in their cost and fast response to current changes [12]. SCs also have the potential for power enhancement in vehicle applications.

SCs are electrochemical capacitors that offer higher power density in comparison with other storage device. They contain an electrical double layer and a separator that separates and holds the electrical charges. The separated charges provide a small amount of potential energy, as low as 2–3 V [13]. The double layer is made of a nano-porous material such as activated carbon that can improve storage density. The capacitance values of SCs can reach 3000 F. Super capacitors or ultra capacitors have a few advantages over batteries such as a longer lifecycle (500,000 cycles), a very high rate of charge/discharge and low internal resistance, which means minimum heat loss and good reversibility [14]. Furthermore, SCs have an efficiency cycle of approximately 90% whereas the efficiency cycle of a battery is approximately 80%. However, SCs are not a source of high energy density. The amount of energy stored per unit weight of SCs is between 3 and 5 W h kg^{-1}, whereas that of a Li-ion battery is approximately 130–140 W h kg^{-1} [15]. Therefore, the combination of SCs with FCs, which have low power density but high energy density, is a practical alternative to improve the efficiency and performance of HEVs. In addition, SCs have a high charging rate, which allows regenerative braking to be used more efficiently. As SCs have the potential to function as an energy storage device in the future, many industries are interested in fabricating SCs with new technology and material design. The lab experiment shows that the energy density of SCs can be reach up to 300–400 W h kg^{-1}, however, future lithium based batteries are projected to achieve densities around 400–600 W h kg^{-1} [13]. The Fig. 1 shows comparison between various energy sources and storage in terms of power and energy density.

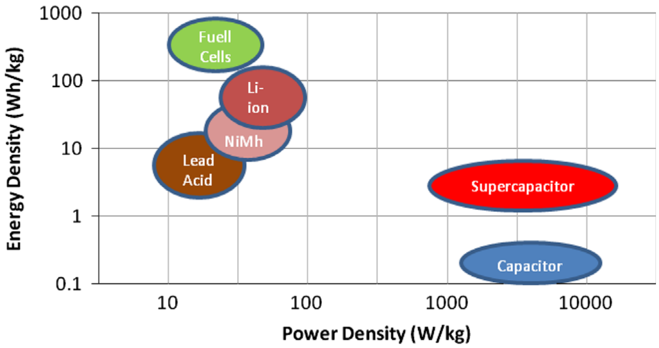

Fig. 1. Comparison between various energy states in terms of power and energy density.

Another important source of renewable energy for the future is solar cells, also known as photovoltaic (PVs). Solar cells are electronic devices that convert sunlight into electricity [16]. The clear advantage of solar cells over conventional fuels is their ability to convert free solar energy from the sun into electricity without generating significant pollution that might impact the ecology of the planet [17]. Solar cells fall into three main categories: single-crystal silicon, which have the highest efficiency of approximately 25%, polycrystalline silicon with 20% efficiency, and amorphous silicon with approximately 10% efficiency [18]. Single-crystal silicon is the most expensive to produce followed by polycrystalline silicon and then amorphous silicon. New solar cell technologies emerging in the market are thin-film cells, gallium–arsenide cells and tandem PV cells. These technologies hold the promise of improving the efficiency and versatility of solar cells while keeping production costs low [18].

Hybridization in using renewable energy is necessary because no single source currently matches the capability of fossil fuels in terms of both energy and power density. Simulation and modeling of HEVs has been extensively reported in the literature. Garcia et al. [19] and Barret [20] have discussed a FC-battery integrated with two dc/dc converters for a tramway. The active control system, which was the novelty of this paper, enabled both the FC and the battery to be coupled in the case of acceleration and regenerative braking. Another research paper on heavy load vehicles analyzed FC hybrid locomotives, which provided a reduction in capital cost [21]. The combination of batteries and FCs for FC hybrid vehicles was studied by Burnett and Borle [22], who indicated that hybridization minimizes the vehicle weight and fuel necessary as compared with FCs alone. The structure of a hybrid system using a SC and a battery was studied by Camara et al. [23], who linked a SC, to a boost converter with simple parallel topology. The parallel-structured hybrid system yielded a reduction in the weight of the vehicle and required less smoothing inductances of the SC current. The application of a SC in FC hybrid power sources was found to be significant as it can assist the FC during its time response to instantaneous power demands, fuel starvations and voltage drops through aging effects [24]. The behavior of HEV systems and internal combustion vehicles under a reference driving cycle has also been studied by Mierlo et al. [25]. An innovative simulation model of FCs, batteries, SCs, flywheels and engine-generators was developed to describe their functionality and characteristics in a vehicle system. The Vehicle Simulation Program (VSP) software, which is undergoing development, shows high simulation accuracy and allows the evaluation of electric vehicles with complex power management strategies or with a hybrid drive train.

A hybridization system using a battery and SC with a PEMFC power source was found to provide improvements in both energy and power density. This work was verified by Thounthong et al. [26] using the following component parameters: PEMFC (500W, 50A), SC (292F, 30V) and battery (68AH, 24V). These researchers proved that the SC manages to balance the energy demand during the load transition period, and this additional storage of energy enhances the quality and efficiency of the power system distribution. Other researchers are interested in the implementation of solar energy, which is usually combined with a battery. Countries including Australia organize the Darwin-Adelaide World Solar Challenge to provide a challenging platform for developers of solar vehicles to showcase their most recent advances [27]. These solar car races serve as an impetus to researchers to develop high-efficiency solar–electric power sources coupled to aerodynamic bodies that minimize mechanical and electrical losses during operation. The difficulty of using a solar-generated source is that it has non-linear *I–V* characteristics and, as a consequence, the maximum power delivery to the load needs to be controlled [28, 29]. This need for maximum power point tracking (MPPT) has encouraged the involvement of many researchers in this area. A new design for a boost converter to improve the efficiency of MPPT has been studied by Khatib and Mohamed [30] and Subiyanto in [31]. Further innovative research involving solar-assisted electric auto rickshaw three-wheelers has also been performed [32] using various hybrid drive trains of plug-in, solar, battery and conventional engines. Studies of renewable energy relating to power electronics [33] and controlling PV applications [34] have also been conducted.

One crucial component in developing a HEV is its EMS, whose main tasks are to maximize, control and utilize generated energy to fulfill the demanded loads. Thounthong et al. [26,35] have reported on the energy management and control system of FCs, solar cells and SCs. A study of series and parallel plug-in hybrid electric vehicles (PHEVs) with dual clutch transmission was performed by Song et al. [36] and Salisa et al. [37] performed modeling and simulation of an EMS for a PHEV. The vehicle performance was compared with a standard U.S. EPA (Environmental Protection agency) drive cycle for highway driving. Bedir and Alouani [38] studied a simple power control strategy for HEVs that controlled the electric motor to provide power in different test situations. The vehicle model was implemented in the ADVISOR vehicle simulator, and preliminary tests indicated a 50% improvement in gas mileage. A study of the EMS of a PEMFC and battery in unmanned aerial vehicle (UAV) electric propulsion was conducted by Karunarathne et al. [39]. The EMS evaluates feedback from the battery, load power and FC parameters and passes this information to the power management system to control the power electronic interface. A fuzzy-based control strategy for hybrid vehicles was developed by Bahar et al. [40] and the EMS for the virtual vehicle design and application was investigated by Ustun et al. [41].

2. Hybrid vehicle energy states

The three categories for state of energy for HEV implementation are energy sources, energy storage and energy conversion device. In the next section, reviews on some of the latest and past technologies implemented are discussed in detail.

2.1. Hybrid electric vehicle energy sources

In following section, three types of renewable energy models applied for the EV are analyzed. They are battery, fuel cell and solar energy model.

2.1.1. Battery model

Lead acid batteries have been used for over one hundred years in electric vehicles. In 1900, 28% of the vehicles in the United States were powered by electricity [42]. Batteries are more efficient as they can store and deliver energy. Lead–acid batteries undergo a reversible chemical reaction that can be described as

$$Pb+PbO_2+2H_2SO_4 \leftrightarrow 2PbSO_4+2H_2O \tag{1}$$

The performance of the battery has a large influence on the state of charge (SOC) of the battery, battery capacity, temperature and aging [43]. A simple battery model consists of constant resistance in series with an ideal voltage source. This simple model does not take the internal resistance and the SOC of the battery into account. The simple model can be improved by replacing R_b with a variable resistance as shown in Fig. 2(a). The linear electrical model measures the linear component for self-discharge, R_p, and various overvoltage in terms of the network circuit $n_m(t)$. Although this model has improved accuracy, it does not consider temperature dependency. Another model developed by Salameh et al. [44] is shown in Fig. 2(b). This mathematical model is simulated in the BASIC program; it accounts for voltage and current drops and differentiates between internal and overvoltage resistances for charging and discharging. A more realistic dynamic model has been approached by adding two more element blocks into the circuit as shown in Fig. 2(c) [44]. In this new dynamic battery model, the V_{oc} relies on the actual discharge current I_B, the energy drawn from the battery E_{cd} and the battery temperature T.

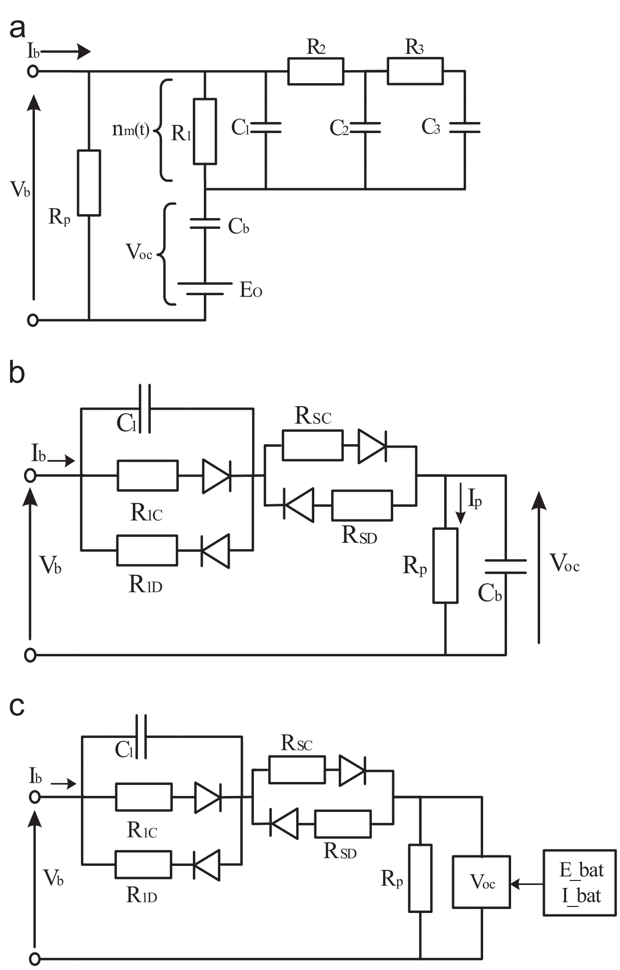

Fig. 2. (a) Improved battery model. (b) Improved battery model by Salameh. (c) Dynamic battery model.

A model of Nickel–Cadmium batteries during discharge has been developed by Sperandio et al. [45] and Green [46]. The Nickel–Cadmium battery supplier provided the discharge voltage curve with fixed current at room temperature. From there, data points were extracted to create the voltage curve as a function of time. The Nickel–Cadmium model is derived from the Paatero [47] model, which defined the open circuit voltage as

$$V_{OC}=a+b \times DOD+(c+d \times DOD)T \tag{2}$$

where T is the battery temperature, DOD is depth of discharge ($DOD=1-SOC$) and a, b, c and d are fitted model parameters, refer [47]. A polymer Li-ion battery is evolved from lithium-ion batteries, with the difference that the electrolyte is composed of a polymeric material instead of an organic solvent [48]. These batteries are widely used in portable applications, such as cell phones, PDAs, digital cameras and laptop computers. The storage capacity of a polymer Li-ion battery is in the range of 150–190 W h kg^{-1} and the power density ranges from 300 to 1500 W kg^{-1}, which is 3–4 times higher than a lead-acid battery [49]. A dynamic battery model that considers the non-linear open-circuit voltage, current, temperature, life-cycle and storage time-dependent capacity to transient response has been proposed by Min Chen and Rincon-Mora [50]. All parameters in the proposed model are extracted through the test system model using a polymer-Li-ion type TCL PL 383562 battery. A computer was used to assist the test system in implementing a constant current–constant voltage to charge the polymer Li-ion battery and another computer-controlled current was used to discharge the batteries.

Zinc–Bromide batteries provide advanced energy storage for vehicular applications. This storage device has high power and energy density of approximately 80–90 W h kg^{-1} and 300–600 W kg^{-1}, respectively [51]. In addition, the life cycle is two to three times higher compared with other conventional batteries [52]. Unlike other batteries, its electrode is not involved in a chemical reaction during charging but acts as a medium for the plating of zinc metal. Then, during discharging, the zinc dissolves back into the electrolyte. The electrochemical reaction that takes place in the zinc–bromide battery is during charging and discharging [51,52].

2.1.2. Fuel cell (FC) model

Fuel cell (FC) is built of anode, anode catalyst layer, electrolyte, cathode and cathode catalyst layer [3]. They can be arranged in series or parallel. DC electrical energy is produced through chemical reaction between hydrogen, H, and oxygen, O, occurs at the anode and cathode as follows:

Anode:

$$H_2 \rightarrow 2H^+ + 2e^- \tag{3}$$

Cathode:

$$\frac{1}{2}O_2+2H^+ \rightarrow H_2O \tag{4}$$

Theoretically, a single cell can generate 1.23 V temperature of 25 °C at 1 atm pressure.

Many empirical models in generating the FC voltage can be obtained from the literature involving the Nernst equation [53,54]. According to Uzunoglu and Alam [55], a single cell of a FC generating voltage derived by the Nernst equation is described as

$$E_{cell}=E_0+\frac{RT}{2F}\ln\frac{P_{H_2}\sqrt{PO_2}}{P_{H_2O}} \tag{5}$$

where E_0 is the standard potential of the hydrogen/oxygen reaction, R is the universal gas constant, F is Faraday′s constant, T is absolute temperature and PH_2 and PH_2O are the partial pressures of water and oxygen, respectively, at the cathode. The output

voltage is the sum of the Nernst voltage, E_{cell}, the activation overvoltage, V_{act} due to the "double layer effect" in the electrical domain and the ohmic overvoltage, V_{ohm} due to membrane resistance as derived as follows [56]:

$$V_{fc} = E_{cell} + V_{act} + V_{ohm} \tag{6}$$

The FC output voltage contains an additional voltage drop, V_{con} due to the reduction in concentration of oxygen/hydrogen in the FC, V_{con} is expressed in [57].

$$V_{con} = -B \ln\left(1 - \frac{J}{J_{\max}}\right) \tag{7}$$

where $B(V)$ is a parametric coefficient that rely on the cell and operation state, J is actual current density of the cell (A/cm^2) and J_{max} rated as 500–1500 mA/cm^3. The FC output voltage is summarized as

$$V_{fc} = E_{cell} + V_{act} + V_{ohm} + V_{con} \tag{8}$$

In a comprehensive dynamic model, PEMFC current/voltage model is developed in [58]. Furthermore, an improved output stack voltage of the PEMFC defined by Chiu et al. [59] refers in [60,61] is as follows

$$E = N\left(E_0 + \frac{RT}{2F}\ln\left\{\frac{P_{H_2}\left(\frac{P_{O_2}}{P_{std}}\right)^{1/2}}{P_{H_2O}}\right\} - L\right) \tag{9}$$

where N is the number of cells in the stack and L is that voltage loss, which consists of activation losses, internal current losses, resistive losses and concentration losses. An empirical PEMFC is developed by Kim et al. [62] to fit the experimental cell potential E against current density. An exponential term was further added to improve the structure of the residual model of the cell potential as in expressed [63] as

$$E = E_0 - iR - b\log(i) - me^{ni} \tag{10}$$

where m and n are constants. A parametric model predicting the performance of a Ballard Mark PEMFC was proposed by Amphlett et al. [64,65]. The model of the V_{stack} is formulated as

$$V_{stack} = E_{cell} + n_{act} + n_{ohm} \tag{11}$$

where n_{act} is activation polarization and n_{ohm} is ohmic polarization.

The FC system in vehicle application is normally connected to the power diode to avoid reverse current flow to the system in a regenerative situation. Then, the FC system is linked to the dc/dc converter, which maintains a constant load voltage.

2.1.3. Solar cell energy model

Photovoltaic (PV) or well-known solar cells are semiconductor devices which convert sunray into electrical energy in form of current. These semiconductor devices have similar characteristics to electronics devices such as diodes and transistor [66]. The equivalent circuit of solar cell can be matched as a current source in parallel with a diode. The I–V characteristic of solar cell is determined from the Shockley equation which the current source I, can be formulated as [67]

$$I = I_L - I_0\left[e^{(qv/KT)} - 1\right] \tag{12}$$

where I_L is light generate current, I_o initial current, V is the voltage, k is the Boltzman constant, q is the electron charge and T is the absolute temperature.

Temperature and irradiance are two factors that affect solar cell's capacity. Increasing temperature reduces voltage value of solar cell at about 2.3 mV/°C [68], whereas temperature variation of the current has minimum effect and is negligible. Irradiance is defined as sum of power from a radiant source falls per unit area. It is directly proportional to the short circuit current of a solar cell [69]. Therefore, higher radiance will increase the photon flux number and thus will generate proportionally higher current.

Solar car park is built to harvest solar energy during midday. Research study by Hannan et al. [70] shows that this system is suitable for light electric vehicle, LEV. For the solar harvesting study case done in Malaysia, below formula is applied:

$$E_{solar} = \int_{t_2}^{t_1} = 0.08t + 64.1dt \tag{13}$$

where E_{solar} is solar energy harvested in one day for 1 m^2 solar panel, t_1 is the harvesting start time and t_2 is the harvesting stop time. After 8 h, solar energy collected is about 1000–2000 W h. From this collected solar energy, ΔE_{solar}, and the vehicle traction force F_{te}, the distance that a specific weight of vehicle could travel, D_{veh}, can be calculated as follows [70]:

$$D_{veh} = \frac{n\Delta E_{solar}}{F_{te}} \tag{14}$$

where n is the electric vehicle efficiency. From the above equation, statistics of distance and the vehicle load values can be presented in a graph as shown in Fig. 3. From this graph, it can be seen clearly that only vehicles with weight of less than 300 kg are suitable to use solar energy from the solar car park.

2.2. Hybrid vehicle energy storage

Energy storage has two important functions – as supplementary source of energy for HEV and as support during regenerative braking. In the following section, review papers on this subject are discussed.

2.2.1. Super capacitors (SC) model

Super capacitors are special capacitors that produce substantial amounts of energy at low voltage. They contain an electrical double layer and a separator that separates and holds the electrical charges. The amount of energy that is stored in a SC can be derived from the energy stored in a capacitor, which can be measured in Coulombs as follows [71].

$$Q_{SC} = \frac{A\varepsilon}{d}V_{SC,OC} \tag{15}$$

where $V_{sc,oc}$ is the open circuit voltage of the SC, A is the plate area, d is the distance between plates and ε is the permittivity. The open circuit voltage of the SC can be expressed in terms of capacitance C_{sc} and charge q_{sc} as [72]

$$V_{SC,OC} = \frac{q_{SC}}{C_{SC}} \tag{16}$$

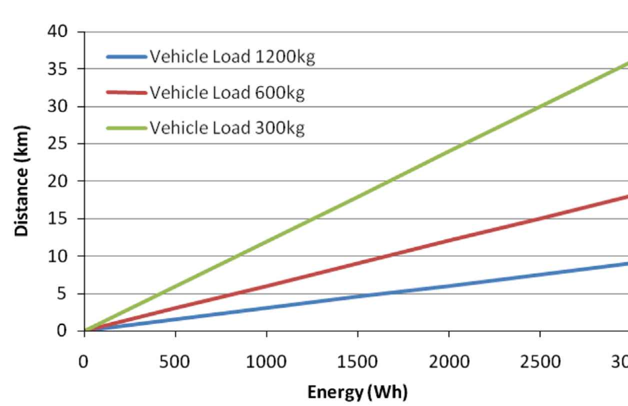

Fig. 3. Distance traveled against energy used for various vehicle loads.

The capacitance C_{sc} can be varied slightly depending on the internal temperature and current of the SC as described by Rotenberg et al. [73]. The charge of the SC is defined as

$$\frac{dq_{SC}}{dt} = -i_{SC} \tag{17}$$

where i_{sc} is the charging current flow. Positive and negative currents correspond to discharge and charge of the SC, respectively. The amount of charge remaining in the SC is defined as *SOC* as follows.

$$SOC = \frac{V_{SC,OC} - V_{SC,\min}}{V_{SC,\max} - V_{SC,\min}} \tag{18}$$

where $V_{sc,max}$ and $V_{sc,min}$ are the maximum and minimum open-circuit voltages. The effective output voltage, $V_{SC,out}$, from the SC is determined by [74] as

$$V_{SC,out} = V_{SC,OC} - i_{SC} R_{SC} \tag{19}$$

where R_{sc} is the line resistance and is assumed to be the same during charge and discharge. The motor-consumed power P_{sc} and the current drawn from the SC are as follows.

$$i_{SC} = \frac{P_{SC}}{V_{SC,out}} \tag{20}$$

The SC energy storage system is designed to aid a battery or FC in the case of high power demand in a hybrid vehicle system. The mathematical modeling of a SC can be related to the basic discharging circuit of capacitor voltage in terms of a resistor and capacitor, RC circuit. The effective discharging voltage is dependent on the initial voltage of the capacitor and the time constant RC which can be described as [74]

$$V_{SC,out}(t) = V_{SC,i} e^{-(t/RC)} \tag{21}$$

where $V_{sc,i}$ is the initial voltage of the SC. One unique feature of a SC is that its voltage is directly proportional to the *SOC*. The amount of energy delivered by the SC is directly proportional to the capacitance and voltage change throughout the discharge as in defined [55]

$$E = \frac{1}{2} C_{SC} \left(V_{sc,i}^2 - V_{sc,f}^2 \right) \tag{22}$$

where $V_{sc,f}$ is the final voltage of the SC and C_{SC} is capacitor value of SC.

The simple equivalent circuit model of the SC [55] consists of a capacitance *C* and a series resistance during charging and discharging, represented by *ESR* or *R* as shown in Fig. 4(a). The parallel resistance, *EPR*, representing the self-discharging losses has an impact only during the long-term energy storage of a SC.

The equivalent circuit proposed by Zubieta and Bonert [75] has three RC branches as shown in Fig. 4(b). These branches have distinct time constants identifying fast current control charges. The parameters are determined by charging the SC from zero to the rated voltage and then observing the terminal voltage during the internal charge distribution for 30 min. The proposed equivalent circuit is designed from repeated measurements using a precisely timed and controlled current source. A study to determine the equivalent circuit equation of an aqueous electrolyte SC was conducted by Yang et al. [76]. That model describes the dynamics of the characteristics of the SC during the process of charging and discharging. The circuit model proposed by Yang is shown in Fig. 4(c) [76]. In contrast to a battery, the aging process of SCs does not rely on the lifecycle stress. The life expectancy of SCs is mostly driven by temperature and cell voltage [77]. A number of SCs can be arranged in series and parallel to form a SC module that is capable of providing a certain amount of energy during acceleration and peak load demand. The SC units that are built in series determine the amount of terminal voltage and the SC units that are connected in parallel determine the value of capacitance. The proper system to combine the SC with the overall load is by implementing a dc/dc converter to raise the voltage to the required voltage load.

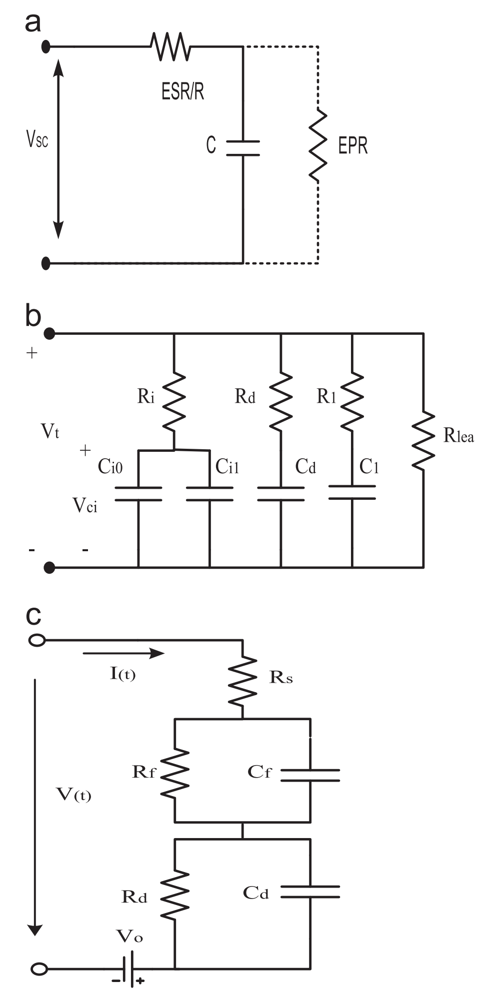

Fig. 4. (a) SC equivalent circuit. (b) SC equivalent circuit proposed by Zubieta. (c) SC equivalent circuit proposed by Yang.

2.2.2. HEV advanced energy storage system

Dynamic control using a switch between the battery and SC has been proposed by Lee et al. [78]. The task was to improve the cycle life and efficiency of the battery in the vehicle. The control algorithm conducts a switch control that relies on the status of the SOC in the battery and the SC. Therefore, the use of the SC is optimized and can improve the life cycle of the battery. The analysis results show that charging and discharging at high current can shorten the battery life [72]. Consequently, the system manages to improve it during engine restart, where the SC supports the high current needed to start the engine and during the charge time, low current is allowed to charge the battery. The switch to charge the battery is turned off if the battery SOC reaches 70%, and the SC will take over the vehicle power line. This feature is a novelty of this system but still needs to be improved, especially to determine the accuracy of the SOC in the battery and SC.

2.2.3. Combination of energy source with auxiliary energy storage for HEVs

The combination of a battery and SC in a multi-power system showed a better regulation of the vehicle traction system dc

voltage compared with a battery as a single power source [79]. The model consists of a ZEBRA battery as the energy dense source and a SC as the power dense source. In the EMS, the SC has two functions that enhance the power demand and extend the battery life by compensating for the high current of the load [71]. The algorithm strategy of the power management system follows three principles: the SC develops the demand current at high acceleration, the battery provides current according to the recommended rate and the remaining current is supported by the SC. These vehicle models were simulated with standard urban driving cycles as well as out-of-city or motorways. The analysis results indicate that the control strategies reduce vehicle fuel consumption and the EMS has a strong value for practical application.

2.3. Hybrid vehicle energy conversion devices

Energy conversion devices are required to supply uniform voltage to the load. Review literatures on the usage of such devices in HEV are described in detail in following section.

2.3.1. Power converter

A power converter levels the voltage of multi-power sources depending on the rated voltage of the DC machine. A dc/dc converter will work with any motor drive technique like inverters to control the power flow in and out depending on the power condition [80]. Power converters that are widely used for HEVs are buck, boost and Ćuk topologies as shown in Fig. 5.

The buck converter used by Castaner and Silvestre [29] is applied to step down the voltage as shown in Fig. 5(a). The input voltage, V_i, is controlled by a switch over a period of duty cycle, D_C and the average output voltage, V_0 can defined as

$$V_0 = \frac{1}{T}\int_0^{t_{on}} V_i(t)dt = D_C V_i \tag{23}$$

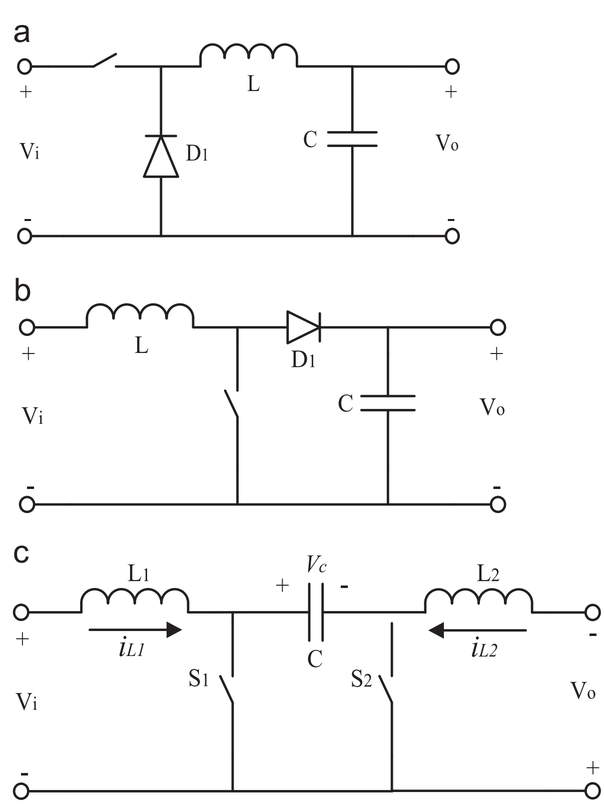

Fig. 5. (a) A PSPICE model of the dc/dc Buck converter. (b) A PSPICE model of the dc/dc Boost converter. (c) A PSPICE model of the dc/dc Ćuk converter.

where T is a constant period and t_{on} is the length of the ON state of the switch.

The boost converter is used to step-up [81] the voltage as shown in Fig. 5(b). The inductor, L stores energy from the input voltage when the diode is in reverse bias. Thus, the energy transferred from the input voltage source V_i to the output voltage source V_0 can be described as

$$V_i - V_0 = L\frac{di_L}{dt} \tag{24}$$

where i_L is the inductor current. The input and output voltage as a function of the duty cycle, D_C, can be expressed as

$$\frac{V_0}{V_i} = \frac{T}{t_{off}} = \frac{1}{1-D_C} \tag{25}$$

The duty cycle, D_C, is given as a fraction of the switching period when switch S_1 is closed and switch S_2 is open. Goekdere et al. [82] also presented a bi-directional Ćuk converter shown in Fig. 5(c). The corresponding model is as

$$\frac{di_{L_1}}{dt} = \frac{v_i - (1-D)v_c}{L_1} \tag{26}$$

$$\frac{di_{L_2}}{dt} = \frac{Dv_c - v_o}{L_2} \tag{27}$$

$$\frac{dv_c}{dt} = \frac{(1-D)i_{L_1} - Di_{L_2}}{C} \tag{28}$$

where all components are referred to Fig. 5(c) which are L_1 and L_2 are inductors, C is capacitor, v_o is output voltage, v_i is input voltage, v_c is capacitor voltage, iL_1 is current through L_1 and iL_2 is current through L_2.

Shuai Lu et al. [83–84] introduced a multilevel converter with cascaded cells (MCCC) in large vehicle propulsion. The new multilevel converter was designed so that it can integrate SCs without a DC–DC converter. The proposed topology contained top and bottom diode-clamped inverters. The top inverter, called a bulk inverter, provided the main DC supply. The bottom inverter, known as the conditioning inverter, was linked to the SCs. The proposed topology managed to regulate the SC voltage thoroughly and a DC–DC converter was no longer necessary.

2.3.2. Improved FC control system

The output power controlling the fuel cell to drive an electric motor through a DC/DC converter was studied by Zenith and Skogestad [85] and Zenith et al. [86]. That study presents a control system based on switching rules in order to control the output voltage of the converter. A common pulse-width modulation control signal is applied to the system although there are other options such as sliding-mode control. The trajectories of the system are presented in the V_C–I_L plane depending on external disturbances such as the working voltage, or the voltage obtained by a FC under a rapidly switching current, and the external load current. A proper model system is satisfied but an unsatisfactory computational efficiency results from the constant time of evaluation and not during the switching algorithm.

3. Hybrid vehicle dynamic model

In this section, a detail review on dynamic model of HEV technology is discussed comprehensively.

3.1. Dynamic modeling hybrid system

Dynamic modeling of a FC/SC hybrid system was performed by Uzunoglu and Alam [55] and Onar et al. [87], who found excellent

characteristics of vehicular application during power demand, steady-state and load switching. The SC assisted the FC if the power sharing technique in the control system was optimized. The analysis models were referred to the profile data from the urban dynamometer driving schedule (UDDS) of the advanced vehicle simulator (ADVISOR) software. The power sharing system was designed to arrange the FC and SC in parallel. The sources were connected to the switch before loading, and the opening of the switches followed the control algorithm, which was dependent on the power demand and deceleration. A PI controller was embedded to the system to improve the power converter system. The dynamic modeling proposed by Onar et al. [87] used wind/FC/SC as the hybrid power generation system. The wind turbine supplied the demand load and any excess of energy was feed to an electrolyzer. The function of an electrolyzer is to generate hydrogen for immediate use by the FC system or for storage [55]. The FC system fulfilled any additional load demand. If the FC and wind turbine reached maximum power, the SC was another option for support of any extensive power demand for short periods only. The dynamic simulation model consisted of a wind turbine, an asynchronous induction generator, power factor correction capacitors, a thyristor-controlled double bridge rectifier, two IGBT inverters, an electrolyzer, a hydrogen storage tank, a dc/dc converter, super capacitors, a fuel cell and a two-winding coupling transformer.

3.2. Dual clutch transmission (DCT) in PHEV

A study of an EMS for a PHEV was performed by Song et al. [37]. Instead of using gear reduction for transmissions such as Salisa et al. [38], this PHEV is equipped with a Dual Clutch Transmission (DCT). The dynamic performance of the vehicle, such as its fuel consumption, was analyzed. The control strategies of this system are more complex as it is built-up with a serial/parallel (S/P) HEV and is based on a driving and braking management system [88]. The driving mode is determined through three parameters: the speed of vehicle, the SOC and the throttle. Parallel braking is applied to the braking system. Two driving cycles, NEDC and UDDS, were used for analyzing the simulation result. The S/P PHEV control system needs less fuel consumption compared with the control strategy developed by ADVISOR and PHEV.

3.3. Improved power-train for HEV

A combination of a FC–SC-battery in a new vehicle topology power-train was introduced by Bauman [89] and Bauman and Kazerani [90]. This superior topology uses a high power dc/dc converter for a FC in parallel with a low power dc/dc converter connected to the battery followed by anti-parallel switch across the diode. Unlike other topologies that use a similar system but without the anti-parallel switch and other conventional systems with a battery with a bidirectional converter parallel to a dc/dc converter for the FC [91], this advanced topology has many advantages including reduction in cost and mass by using a low-power boost converter, a high-efficiency path during charging and discharging of the battery and a SC that provides the majority of the current of the transient power, which prolongs the battery lifetime and offers simple modification to a PHEV.

3.4. Dynamic modeling FC powered scooter

Chao et al. [92] in Taiwan conducted a simulation study of a motor scooter powered by a fuel cell and tested the non-linearity form of the power signal in electronics and electrical machines. Factors such as conduction and switching losses and temperature stress on the semiconductors were simulated [93]. The fuel cell scooter simulation included an analysis of the power systems of the scooter, i.e. the battery, electrical and electronic components, the inverter and the permanent magnet synchronous motor (PMSM) and field oriented control (FOC) model. A position encoder can be used to detect the rotor position and then switch the phases to measure the phase current for modeling FOC applications. A hardware test was performed to verify the simulation data. For example, mileage simulations predicted that a fully-fueled vehicle has a travel range of 80 km. In fact, a range of 100.8 km was achieved in actual tests. The fuel consumption simulation predicted a rate of 1.6 g hydrogen/km against 1.34 g hydrogen/km achieved in actual trials. These studies provide useful information on the design of fuel cell scooters not just when they operate under idealized theoretical conditions but also under realistic test situations. A cost analysis provides further evidence in support of the development of a commercially viable FC scooter [92]. As a result, future studies should consider the infrastructure of FC stations.

4. Characteristic and types of hybrid vehicle

The characteristics and classification of a hybrid vehicle alongside with three examples is presented in this section. The three HEV examples are auto-rickshaw, plug-in HEV and REVS-based HEV. At the end of the chapter, the Adaptive Neuro-Fuzzy Interference System will be described.

4.1. Characterization of HEV

A study of the characteristics of a HEV was performed by Lukic et al. [94,95]. HEVs have been categorized by their mechanical connections in series, parallel or series/parallel. For a series HEV, the electric motor is responsible for the propulsion power. Meanwhile, the engine is used to recharge the battery. For a parallel HEV, both the electric motor and engine support power to the drive train. In a series/parallel HEV, an additional planetary gear set is used. This mechanical device allows energy flow to the drive train either in series or parallel. Lukic et al. [94] introduced the concept of a hybridization factor, HF, to level the hybridization of a HEV. The classification of HEVs by HF is categorized between $HF=0$ (ICE vehicle) and $HF=1$ (electric vehicle) where HF is expressed as

$$HF=\frac{P_{EM}}{P_{EM}+P_{ICE}} \tag{29}$$

where P_{EM} is the peak power of the electric motor and P_{ICE} is the peak power of the ICE.

In the automobile industry, the manufacturer produces different types of HEVs to improve vehicle fuel economy and efficiency. These types can be classified as follows [94,95]:

- *Micro-HEV ($HF<0.1$)*: Micro-HEVs use limited power of the EM as a combination of starter and alternator to provide a fast start/stop operation and then allowed the ICE to propel the vehicle, which means that the ICE can be stopped when the vehicle is in a standstill condition. As a result, it saves the fuel consumption of the vehicle by approximately 10%, especially when traveling in urban city areas.
- *Mild-HEV ($HF<0.25$)*: Mild-HEVs have additional functions that can use the EM to boost the ICE during acceleration and can perform regenerative braking as well. However, the electric machine is not capable of driving the vehicle alone [96]. It can save approximately 10–20% of fuel consumption.
- *Power-assisted HEV ($0.25<HF<0.5$)*: Power-assisted HEVs can provide substantial electric propulsion to support ICE. For short

distances, the vehicle can be turned into a fully electric system or become a zero-emissions vehicle, ZEV. The propulsion of the vehicle can also be guaranteed by the ICE alone. Fuel economy may be improved up to 50%.

- *Plug-In HEV (HF > 0.5)*: A PHEV uses a battery as the storage device. The battery is recharged from a residential power grid. These types of vehicles are accommodated with an on-board generator and ICE [78].
- Vehicle that does not implement ICE such as Hybrid fuel cell vehicle, HFCV or battery EV, BEV (HF=1): BEV or PHEV, are grouped in this category. HFCV is considered as an electric vehicle since FC is a green technology component. On board the vehicle, stored hydrogen can be extracted by a reformer. The electricity gained by the FC will drive the electrical machine and normally be assisted by a SC to improve its low power response.

FC development has been significantly researched but the major obstacles for the commercialization are cost, hydrogen storage and refueling infrastructures. Because oil prices are still affordable, HFCV is not yet a favorable option.

4.2. Auto rickshaw

Three-wheel vehicles (Auto Rickshaws) are a very popular and inexpensive transportation option in many Asian countries. They are mostly used in cities for short-distance traveling, have a capacity of 5–7 kW and are powered by ICEs. Recently, as a result of green technology concerns, small HEVs have been introduced with a different power system concept where the ICE is integrated with a battery and solar cells. A correlative analysis study of a three-wheeled rickshaw with various drive trains of hybrid configurations has been successfully completed by Mulhall et al. [97] and Mulhall and Emadi [98]. Four types of drive trains were studied: (i) drive trains with direct drives, (ii)drive trains with one electric motor, (iii) drive trains in parallel hybrid configuration, and (iv) drive train – conventional rickshaw with a solar-assisted auxiliary unit. For the electric vehicles, type (i) outperformed type (ii) because it used a direct-drive propulsion system; however, it is expensive. Type (iii) combines a motor and engine and type (iv) is a conventional auto rickshaw [97]. The simulation results indicated that an all-electric rickshaw can achieve acceptable range with a single charge. In addition to the work on the vehicle model, the recharge infrastructure has also been considered [98]. The goals of this study were to accomplish efficient and effective battery-swap services, maximized usage of renewable sources and the design of a no-grid-interaction infrastructure.

An analysis of the electric propulsion motor for an auto rickshaw was also conducted. Various sizes and speeds of the motor were simulated using the advanced vehicle simulator (ADVISOR) to evaluate vehicle efficiency, gradeability and acceleration [99]. A driving cycle test from a real auto rickshaw in India was gathered using GPS data and was implemented in the simulation. Motor power, torque and speed were scaled before simulation. The gear ratio (GR) is set according to the different motor speeds for high motor/controller efficiency. An increase in motor size resulted in a slight drop in the motor/controller and vehicle economy and an increase in the maximum acceleration [97]. When the motor speed increased, both the motor/controller efficiency and vehicle economy rapidly decreased. An analysis of the relationship between motor size, speed and gradeability revealed an inconsistent trend. When the motor size increased, the top speed showed a slight drop or increase for specific rpm motors, while the gradeability tended to increase. The acceleration time increased as the motor size decreased.

4.3. Plug-in HEV

Salisa et al. [100] developed a simulation model of an EMS for a Plug-in Hybrid Electric Vehicle (PHEV). The vehicle control strategy components that were required an energy storage system, an electric motor, a power control unit and an ICE. The PHEV simulation models in MATLAB/SIMULINK allowed the analysis of the performance, emissions and fuel economy of the vehicle [37]. The analysis result was verified with the software tool ADVISOR, developed by the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL).The PHEV vehicle model was parameterized for an average sedan car that consisted of an energy storage system (ESS), an electrical machine, a combustion engine and transmissions. The driver controller was an integral and derivative (PID) controller that maneuvered the vehicle to the desired vehicle speed [100]. The ESS contained a battery P_B and a super capacitors bank P_{SC}. The total power of the ESS, P_{ESS} was defined as

$$P_{ESS}(t) = P_B(t) + P_{SC}(t) \tag{30}$$

The battery model designed by Salisa et al. [99] consists of four blocks, where the open voltage of the battery pack is V_{OCpack} and the internal resistance of the battery pack is R_{pack}. The voltage drop V_{out} of the battery is calculated using Kirchoff's law as:

$$V_{out} = V_{OCpack} - R_{pack} I_{out} \tag{31}$$

The summarized output battery current I_{out} with relation to the power demand P_D can be defined as

$$I_{out} = \frac{V_{OCpack} - \sqrt{V_{OCpack}^2 - 4R_{pack}P_D}}{2R_{pack}} \tag{32}$$

The calculation of the battery residual capacity defined in terms of the SOC can be calculated as

$$SOC = \frac{(MAX_{capacity} - AH_{used})}{MAX_{capacity}} \tag{33}$$

where $MAX_{capacity}$ is maximum battery capacity and AH_{used} is amount discharged current from battery.

The calculation of the voltage and output current of the SC model is similar to the battery model. The difference is the value of the total internal resistance of the SC changes during charging and discharging of the SC [77]. The fuel economy and emission ($FE_{combined}$) of the University of Technology Sydney UTS-PHEV were analyzed not only in a drive cycle test, such as HWFET or UDDS and combinations of both drive cycles, but also in a partial charged test (FE_{PCT}) and fully charged test (FE_{FCT}). Weighing city usage at 55% and highway usage at 45%, the combined fuel economy can be defined as

$$FE_{combined} = \frac{1}{\frac{0.55}{FE_{city}} + \frac{0.45}{FE_{highway}}} \tag{34}$$

The FE_{PCT} test measures the fuel economy and emission of the vehicle when the system is at a low threshold operating level while the FE_{FCT} is performed for the full operating system with the SOC at 100% [100]. The fuel economy of the FE_{PCT} is measured in terms of the volume of fuel in gallons, V_{fuel} and the distance in miles, D.

$$FE_{PCT} = \frac{D}{V_{fuel}} \tag{35}$$

The fuel economy of the FCT is configured by

$$FE_{FCT} = \frac{D}{V_{fuel} + \frac{E_{charge}}{E_{gasoline}}} \tag{36}$$

where E_{charge} is the electrical recharge energy in kWh and $E_{gasoline}$ is a constant equal to 33.44 k W h gal^{-1}.

The EMS controls the distribution of the power system components such as mechanical braking, regenerative braking, motor only driving, battery recharging, engine and motor assist and engine only mode depending on the power demand in acceleration and deceleration and the SOC level [37]. The analysis results indicate that the PHEV simulation meets the target drive cycle of the ADVISOR in terms of vehicle speed, force and output power. In fact, the PHEV simulation have shown better results in the SOC level as it has a better EMS and can capture more regenerative braking energy.

4.4. REVS based HEV

Renewable energy vehicle simulator (REVS) provides visual programming interface to configure HEV and PHEV model system and EMS strategy. The model system REVS consists of several components including an electric motor, an ICE, fuzzy control strategies and renewable energy sources that can be simulated in different drive configurations. The ICE is simulated by IDEAS. A model of series and parallel HEVs in REVS has been designed by Ghorbani et al. [101] to analyze the EMS and dynamic response of the system. The vehicle characteristics are derived from the model Toyota Prius [96]. The power split device in the ICE supply driving force to propel of the vehicle and a generator, which generates the electricity to charge the battery. A power controller coordinates the EMS strategy by implementing fuzzy logic to compute the power flow based on the inputs of the accelerator pedal and SOC of the battery [101]. For the vehicle to follow the desired velocity, a low pass filter is implemented together with the fuzzy logic controller. The results of the study indicate that the system model managed to follow the EMS strategy.

4.5. Adaptive Neuro Fuzzy Interferences System in unmanned electric aerial vehicle

Power and energy management systems for a FC and battery driven system, as studied by Karunarathne et al. [39], are designed for electric propulsion systems replacing ICE. The system has three components: the EMS, the power management system (PMS) and the power electronic interface (PEI). The EMS uses strategies that optimize the energy usage whereas the PMS develop policies for the PEI to control the DC/DC converter. The decisions of the EMS are based on the feedback input of the battery SOC and the power load to optimize energy sharing of the sources [87]. Command signals executed by the EMS are passed onto the PMS, where a switching plan policy is defined. Simultaneously, the EMS is responsible for the control of the FC system to prevent oxygen starvation [35]. The PEI consists of a DC/DC converter for the FC and battery, receives signal input from the PMS and boosts up the demanded energy load. The novelty of the study is the introduction of an intelligent power management (IPM) system. The task of the IPM is to decide the operating power of the FC based on a Fuzzy Logic Rule Base System. In the case of nonlinear power characteristics of the hybrid system, an Adaptive Neuro Fuzzy Interferences System (ANFIS) is applied.

5. Control and component system of HEV

The content of following sections will focus to discuss about applicable control system and energy management system for both HEV as well as multi-sources energy model.

5.1. Control system

Control system serves to coordinate power flow from source to load. An optimized control system will improve vehicle efficiency, stability and performance. Selected review papers on this subject will be discussed in the next section.

5.1.1. Energy management system for HEV

The objective of the control system in an EMS is to improve the efficiency of the vehicle system. Without efficiency in the control system, the performance of the hybrid system is at an unsatisfactory level because each power source has capacity limitations. Selecting which power source to use or when a combination is necessary requires an intelligent control system [102]. A powerful control system is essential for a good energy management system. For example, in order to optimize the FC/SC system [55], a control algorithm was designed that relied on the power demand condition and is summarized as follows [102,103]:

- In a low power demand condition, the FC system will generate power to the load and any excess power will recharge the SC.
- In a high power demand condition, both the FC and SC will generate power.
- The generating power of the FC must be greater than 700 W to avoid FC activation losses.
- The release energy from regenerative braking will charge the SC.
- The buck-boost dc/dc power converter is used to provide a constant load bus voltage.

5.1.2. Control strategy for vehicle applications

Another study of control strategy was conducted by Garcia [19] and Miller et al. [21]. They investigated the application of a FC-battery hybrid system for tramways, focusing on the configuration of a FC-battery powered system for a tramway in Metro Centre in Seville, Spain. The research involved designing an EMS with fixed reference signals for the FC dc/dc boost converter, electrical motor drives and energy dissipation in the braking chopper. The tramway EMS optimized the generated energy system in response to demand. It also managed the operation of the braking chopper when regenerative braking occurred. The EMS was controlled based on three levels of SOC as high (60%–65%), medium (42%–60%) and low ($<$40%), respectively Fig. 6.

5.1.3. Control system for multi-sources energy model

Study on control system for multi-sources energy HEV was conducted by Hannan et al. [103] on a vehicle model is powered by battery, FC and SC. The control algorithm was developed to fulfill various driving conditions. The logic design for the control algorithm is shown in Table 1. For validation purposes, simulation

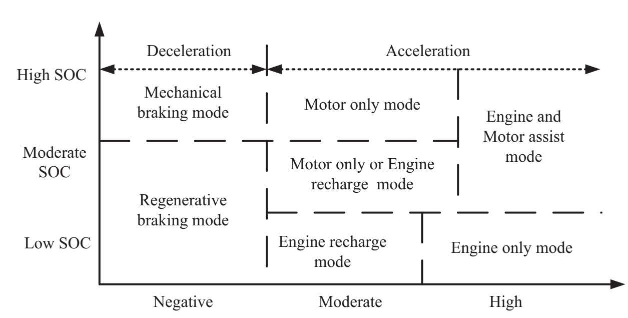

Fig. 6. EMS's operation chart on PHEV.

Table 1
Logic control algorithm for various driving conditions.

State	Super-capacitor	Fuel cell	Battery	Condition
1	0	0	0	Off operation/regenerative braking
2	0	0	1	BC is high; PD is Low and PO is low
3	0	1	0	BC is low; PD is low and PO is low
4	0	1	1	BC is high; PD is high and PO is low
–	1	0	0	– (Not possible)
5	1	0	1	BC is High; PD is Low and PO is High
6	1	1	0	BC is low; PD is low and PO is high
7	1	1	1	BC is high; PD is high and PO is high

BC=battery SOC; PD=power demand; PO=pedal offset.

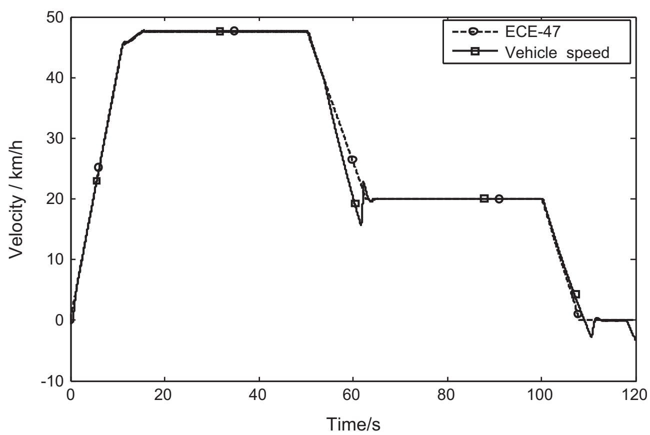

Fig. 7. Simulation result of vehicle speed against the ECE-47 drive cycle.

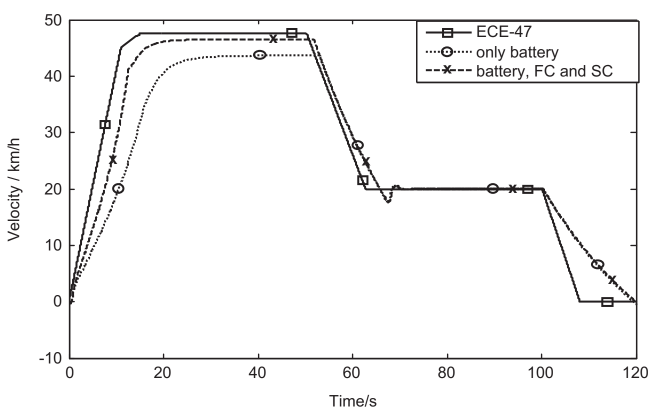

Fig. 8. Simulation result of single and multi-sources energy against the ECE-47 drive cycle.

model was tested against the ECE-47 drive cycle. Results accumulated support the fact that multi-sources vehicle with smart control strategy could be one of the solution for efficient and green vehicle technology for the near future. For reference, simulation results are presented in Figs. 7 and 8 [70].

5.2. Applied HEV component model in control system

5.2.1. DC machine

Yang et al. [104] introduced a novel EMS for an electric scooter with an electronic gearshift and regenerative braking. The test scooter was driven directly by a four-phase axial-flux DC brushless wheel motor. The task was to convert electrical energy into

Table 2
DC machine/motor parameter.

DC machine parameter	Values
Rated voltage, v (field and armature)	120 V
Armature resistance, R_a and inductance, L_a	0.4382 Ω, 0.006763H
Field resistance, R_f and inductance, L_f	84.91 Ω, 13.39H
Field armature mutual inductance, L_{af}	0.7096H
Total inertia, J	0.2053 kg m^2
Viscous friction coefficient, B_m	0.007032 N m s
Coulomb friction torque, T_f	5.282 N m

mechanical energy to drive the vehicle and that of the latter was to manage the multi-sources and restore energy during regenerative braking. Faiz and Moayed-Zadeh [105] proposed models for the non-linear behavior of SRMs including: the non-linearity of B/H characteristics in ferromagnetic materials; the flux-linkage reliability on rotor position and stator winding current; Electrical input system from one point. Their SRM graphical models are based on Finite Element Model (FEM) analysis that ensures the results and analysis derived from motor designed. MATLAB SIMULINK offers a separately excited DC machine block for simulation in the EV system. The mathematical formula for an excited DC machine is described in [105] and depicted in Table 2.

5.2.2. Vehicle system

The physical model of the vehicle system is developed based on applied load during motion. Vehicle dynamic models have been explained in many literature reviews as in [41,42]. The characteristics of the vehicle and the parameter coefficients that concern the vehicle are changed, depending on the vehicle design and the movement situation. Forces that occur during the movement of the vehicle, including the motor torque and speed, are evaluated. In some vehicle systems, the motor speed and torque are not directly linked to the linear movement of the vehicle but instead through the gear ratio and the radius of the vehicle drive wheel. The simulations model of the vehicle system developed by Williamson et al. [107,108] is tested under the Federal Urban Driving Schedule (FUDS) and High Way Fuel Economy Test (HWFET) drive cycle and their empirical model expresses instantaneous power generation. An example model of vehicle system that is based on the MATLAB/SIMULINK is presented in the Table 3 [106].

Important criteria such as technology, renewable energy source and electrical characteristic from all research studies found in chapter 1–5 are summarized and compiled in Table 4. Table 5 on the other hand makes comparison of the research methodology including the advantages and disadvantages of each approach.

6. Current challenges and problems

Hybrid electric vehicles are the promising future transport option for the next generation. As the price of crude oil has increased substantially over the past decades, consumers have been forced to seek alternatives energy sources for transportation [108]. In contrast to hybrid vehicle with ICE, a BEV and PHEV are more energy efficient and emit near to zero hazardous emissions. Large group of researchers have contributed to improve efficiency and performance of PHEV [109]. From existing research, these technologies capable to perform HEV well, however, the reliability and the intelligent systems are still not up to the mark. Thus, there are many factors still need to be considered before HEV opened

full swing in the market as well as number of current challenges are as follows [110]:

- Renewable energy sources for vehicle applications have drawbacks in energy and power density.
- The cost of these vehicles is still high.
- The infrastructure of refueling stations needs to be measured. For a light vehicle, a small storage tank is required. As alternative, exchange storage tank can be introduced.
- A detailed study of hydrogen production for FCs, including delivery and storage tank systems, needs to be conducted. According to the Bossel (2004) [111], study of these works including refueling infrastructure has already done. That will cost trillions of dollars to become reality.
- For plug-in BEVs, recharging is time-consuming and, thus, a study of rapid recharging systems is necessary. The development of lithium-ion batteries which have less weight and short recharge time has give positive impact for cars manufacturer in producing BEV and hybrid vehicles. Cars like Chevy Volt, Tesla S and Nissan leaf is the example comes from the new battery technology.

All these issues need to be addressed properly before BEVs and HEVs are ready for the public market.

Table 3
Characteristics of the vehicle's dynamic model parameters.

Vehicle model parameter	Values
Tire radius, r	0.26 m
Gear ratio, G	2
Vehicle mass + passengers	240 kg
Frontal area, A	1.2 m^2
Drag coefficient, cd	0.75
Rolling coefficient, u_r	0.009
Air-density, d	1.25 kg m^{-3}
Gravity acceleration, g	9.81 m s^{-2}

6.1. Energy storage

The main function of the energy storage in EV is to store electric energy during rechargeable and regenerative braking. The most common energy storage devices in EV are battery and SCs [1,2]. Batteries typically consist of one third or more vehicle weight and size. They also have low life-cycle that required maintenance in 1–2 years. These devices can provide readily electric power/energy in limited capability and then they needed to be recharged again. The United States of Advanced Battery Consortium plays a major role in developing and commercializing

Table 4
Summaries of the hybrid vehicles parameters and technologies.

No.	Vehicle description	Research technology	Renewable energy	Operating voltage (V)	Power load	Efficiency (%)	Ref.
1	HEV-auto richshaw	Proposed four drive train such as direct drive, one electric motor, parallel hybrid configuration, and conventional with solar assist.	Solar, battery	48	5–7 kW	77 – E 73 – M	[29,30]
2	Vehicular application	Power sharing FC and SC with control algorithm. PI controller to improve power converter system	FC/SC	188	58 kW	Better ES	[44]
3	PHEV	EMS distribute power system and PID controller for propulsion	Plug-in	~300	43 kW ICE 75 kW EM	UTS PHEV > PHEV – FE	[36,37]
4	Hybrid power generation	Simulation power generation with electrolyze and hydrogen storage tank.	Wind/FC/SC	400	110k W	Better ES	45
5	PHEV-ICE	Vehicle equipped by DCT and control strategies with serial/parallel/ (S/P) HEV	Battery	305	29 kW-EM1 55 kW-EM2	4.98 – FE	35
6	FCV	Simulate FC scooter with application of FOC control system.	FC, Battery	< 48	3.6 kW	43 – CS	46
7	Automotive application	Proposed HEV classification, review energy sources and EV topology connection	FC,SC, battery, flywheel	–	–	–	[42,43]
8	HEV	Battery and SC in multi-power sources	Battery, SC	~300	32 kW	Improved ES	[54]
9	HEV, PHEV–ICE	Study Renewable Energy Vehicle Simulator (REVS) for HEV and PHEV	Battery	400	57 kW ICE 50 kW EM	Better – FE	[49]
10	HEV	New vehicle topology power train with high power dc/dc converter FC and low dc/dc converter battery	Battery, FC, SC	425	40 kW	11.14 – CS	[51,52]
11	UAV	Design EMS, PMS and PEI with IPM system including Fuzzy logic and ANFIS	Battery, FC	24	2 kW	Improved ES	[39]
12	Automotive application	Output power controlling for electric motor	FC	200	> 10 kW	> 20 FC	[55,56]
13	HEV	Dynamic controlled energy storage	Battery, SC	12/42	< 6.5 kW	Better ES	[57]
14	Transport application	EMS for hybrid tramway in power distribution and braking operation	Battery, FC	625	4 × 120 kW	Better ES	[17]
15	HEV	Multilevel converter integrating SC for vehicle propulsion	Battery, SC	420	> 250 kW	Improved ES	[92–93]
16	HEV	Solar/hydrogen hybrid power system combining battery/FC for HEV	Battery, SC, FC, solar	42	15 kW	Better ES	[20]
17	HEV	Investigating FC and SC based on electric bicycle	FC, SC	36	300 W	45 FC	[87]
18	HEV	EMS in solar car race	Solar, battery	300	3.5 kW	91 EM	[41]
19	EV	EMS in directly-drive vehicle	Battery, SC	48	1.85 kW	70	[95]
20	HEV	HEV in virtual test bed environment	Battery, FC, SC	> 250	> 50 kW	Improved ES	[91]
21	HEV	Control strategy in power management with various converter topology	Battery, SC	~270	216 kW	Better E, ES	[21]
22	Automotive application	Study on hybridization of battery/FC/SC	Battery, FC, SC	42	10 kW	High ES	[6, 23, 33]
23	HEV-ICE	Control strategy based on Fuzzy logic control	Battery	> 250	30 kW EM	Better ES	[40]
24	HEV-ICE	Analysis of drive train efficiency	Battery	~300	41 kW ICE 75 kW EM	Better M, ES	[98,99]

E – electrical, M – mechanical, FE – fuel economy, CS – cost saving, ES – energy saving.

Table 5
Outline methodology and advantages/disadvantages from selected review paper.

Title	Methodology	Advantages/disadvantages
Solar-assisted electric auto rickshaw three-wheeler	New rickshaw design is simulated by using ADVISOR and is linked to MATLAB/SIMULINK to analyze performance, economy and emission rate.	Adv: zero emissions. Good vehicle efficiency and performance for small size motor. Disadv: a complex drive train design and high cost of controller.
An EMS for a directly-driven electric scooter	Experiment setup with six components including a core FPGA controller. The NI Labview system record real-time measurement.	Adv: regenerative braking is 20% higher and prolonged battery lifecycle. Disadv: vehicle complexity.
Modeling of a Taiwan FC powered scooter	FOC is applied to control power electronics to drive permanent magnet synchronous motor. Drive control and vehicle characteristics embedded C-code for DSP is simulated.	Adv: low cost and deliver better performance for vehicle. Disadv: no regenerative braking system.
Electrical characteristic study of a Hybrid PEMFC and SC	Small size PEMFC combined with SC for bicycle is set up. PIC controller is developed for control system to regulate DC bus voltage and the load.	Adv: SC manages to protect FC during sudden load changing and this prolong FC lifetime. Disadv: no regenerative braking system.
Modeling and Simulation of an EMS for PHEVs	Analyze of power flow and vehicle size are simulated in MATLAB/SIMULINK. Results are compared with ADVISOR PHEV.	Adv: EMS mode is effective and show positive fuel efficiency.
Modeling and Simulation of a Series Parallel HEV Using REVS	All vehicle components are integrated in a model and perform graphical simulation in MATLAB /SIMULINK. Support by Fuzzy controllers for data analysis. A complete system is called REVS.	Adv: offers data analysis from new designed HEV or PHEV.
SCs for power assis-tance in Hybrid Power Source with FC	Several energy mode operations are introduced. Control management strategy consists of inner loop controlling structure before being linked to DC converter	Adv: FC performance improves and SC reduces fuel consumption.
Modeling and control FC – battery hybrid system	EMS controls all electrical components including motor controller. Adaptive control based on states is designed and the system is simulated in MATLAB/SIMULINK	Adv: zero emissions. Good vehicle efficiency and performance for small size motor.

advanced battery [112]. The research seeks to increase the energy and power capability, extend life time, size, weight and cost of the batteries. SCs provide one tenth of electric energy consumed by battery and normally designed for secondary storage or power assistance. The increasing of SCs storage capacity certainly shortens the recharging time of HEV. Since the voltage of SCs is directly proportional to SOC, an electronic controller is required to compensate the wide range of discharge voltage. New technology is required to solve the drawback of both storage devices [35,36]. The proper control of the energy storage can be seen for both storage devices as a challenge and opportunity to discover in the power and energy management system.

6.2. Power or energy management system

An optimized integrated system of power and energy management system is another approach for EV application. The system aims to optimize the performance of the overall vehicle system through coordinate multi-power sources. These are the critical parameters to ensure a high achievement of the power or energy management system [70].

6.2.1. System stability

Automations power system in HEV employs power switching unit, converters which are susceptible to parameters such as temperature, switching-off power electronics and load variation [34]. This disturbance from a change power demand, loss of power sources, short circuit and open circuit caused instability of the dynamic power system as all power devices and sources are interconnected [74]. In order to maintain system stability, the EMS must be well-designed properly according standard operation of power and distribution system to ensure the system operates at its nominal power.

6.2.2. Uninterruptible power availability

On-board electronics devices of HEV must be consistently supply during operation. For a safety restraint, a backup power source is required in case of a short time primary power source interruption [112]. In addition, this backup power source can support power demand during critical power load requirement.

6.2.3. Dynamic resource allocation

The peak and power demand load differs depend on situation and condition of the vehicle. PMS and EMS should be able to optimize the available sources on-board and consequently manage them properly to meet requirement load. The task will be more complex when two or more power sources are available on-board. This management system must be followed by intelligent control algorithms that rely on priorities and schedules [112].

6.2.4. Power quality

The power quality in automotive power system guarantees the safety, stability and proper operation of power devices unit and electric loads [74]. A high power quality manages to reduce noise and various transient during large current switching. Moreover, inadvertently disconnect from the large load may lead of voltage spike.

Thus, it is important to study these issues in designing power or energy management system to pursue maximum energy efficiency, achieve high vehicle performance and maintain low emission level [113].

6.3. System configuration and drive train structure

Hybrid vehicles have two or more sources of energy in the vehicle. One is the main power source and the other is assist power source. The vehicle propulsion systems in HEV normally designed in series, parallel and series-parallel [106]. A series hybrid drive train is not so complex and cheaper compare to the parallel and series-parallel configuration. However if ICE is used, a series hybrid may suffer some disadvantages such as additional generator, maximum size of traction motor and less efficient after twice energy converting. This research study is important for selection in sizing of the HEV depend on cost, power and application [107]. The DC dual-voltage system is the some of the interesting undergoing research develop by the automotive companies especially for HEV. This dual-voltage architecture manages to achieve a practical, dependable, low-cost and efficient in power distribution. Today, it becomes important challenge for automotive industries.

6.4. Power electronics

Power electronics is the power switching devices which associated with control system to drive electric motors [31]. The requirements of these devices play a major role in HEV to improve drive system efficiency in vehicle driving range and fuel economy. In addition, the reliability and affordability of these systems may lead HEV to the market. The task of the system includes converters/inverters, control, power switching and integrated to any electronics devices [34]. The issues such as switching loses during turn-on and turn-off, switching frequency of PWM operating mode, noise and EMI consideration, durability of the switching devices etc are the technical challenges of power devices.

6.5. Motor generation

Main component of an electric vehicle (EV) is the electric motor itself. The commonly used series wound brushed DC motors, AC motors, brushless DC motors, and permanent magnet motors are not up to the mark due their higher torque, complex speed control mechanism, expensive controllers and narrow rpm band [113]. Thus, for the next generation motor, a high efficiency, less complex controller, broader rpm band, a compact and ruggedness of the motor is necessary. In-wheel motor where motor and wheel are together is another option to increase efficiency of EV and to reduce cost [114]. In addition, the implement of in-wheel motor shows some advantages as mechanical part like vehicle transmission, gear and axle can be neglected. The application of in-wheel motor has been seen in electric scooter and solar car design [41–43].

The world is still depending on the crude oil as energy source for transportation. Each year the demand of fossil fuel is never decline but increase linearly. As we know that crude oil is not last forever and will be shortage in coming years. The fact is the maximum oil production could be decreased within 5–10 years [1,2] if there is no other new area of crude oil is discovered. This can lead a huge margin between offer and demand that give a great impact in the oil prices. As a result, a renewable energy for vehicle is the alternative power generation near future.

7. Conclusion

Hybrid vehicle systems powered by renewable energies are very important research interest of the researchers. Currently, few projects in the world involved in developing in this technology. The purpose of this review paper is to explain detail about hybrid vehicle technologies and their short comes. At the same time, attract researchers involved in this field for finding new solution. Some related studies that have been discussed are renewable energies technology, energy management system and other related topics. Various form of model and description glance the overall system of HEV rather than to specific technology. This will initiate for further advance of HEV technology and creativity. Theoretically, current literature reviews suggested that BEV and PHEV have high potential to be our next generation of transportation. Research shows that EMS supports these hybrid vehicle power systems by managing current flows and coordinating multi power sources efficiently. These improve the performance of hybrid vehicle and utilize conservation of energy. Other study in energy-saving scheme by hybrid vehicle is the used of regenerative braking energy by braking chopper and multi-level inverter. Besides of intelligent control system, power electronics converters and electric propulsion which has been explained are the critical components for hybrid vehicle. Finally, mathematical models of HEV that develop by researchers have been successful simulated, are the important tools in investigating of hybrid vehicle performance. The continuous developing of technology will certainly push HEV for the future transportation. The innovative scientific research in reducing the manufacturing cost and the overall system may helps in booming the HEV market.

References

[1] Jorgensen K. Technologies for electric, hybrid and hydrogen vehicles: electricity from renewable energy sources in transport. Utilities Policy 2008;16:72–9.
[2] Mierlo JV, Maggeto G, Lataire P. Which energy source for road transport in the future? A comparison of battery, hybrid and fuel cell vehicles Energy Conversion and Management 2006;47(17):2748–60.
[3] Basu S. Recent trends in fuel cell science and technology. New Delhi: Springer; 2007.
[4] Erdinc O, Uzunoglu M. Recent trends in PEM fuel cell-powered hybrid systems: investigation of application areas, design architectures and energy management approaches. Renewable and Sustainable Energy Reviews 2010;14(9):2874–84.
[5] Duerr M, Cruden A, Gair S, McDonald JR. Dynamic model of a lead acid battery for use in a domestic fuel cell system. Journal of Power Sources 2006;161(2):1400–11.
[6] Brouwer J. On the role of fuel cells and hydrogen in a more sustainable and renewable. Journal of Current Applied Physics 2010;10(2):9–17.
[7] Wee JH. Applications of proton exchange membrane fuel cell systems. Renewable and Sustainable Energy Reviews 2007;11(8):1720–38.
[8] Wee JH. Contribution of fuel cell systems to CO_2 emission reduction in their application fields. Renewable and Sustainable Energy Reviews 2010;14 (2):735–44.
[9] Garcia CA, Manzini F, Islas J. Air emissions scenarios from ethanol as a gasoline oxygenate in Mexico City Metropolitan Area. Renewable and Sustainable Energy Reviews 2010;14(9):3032–40.
[10] Rao Z, Wang S. A review of power battery thermal energy management. Renewable and Sustainable Energy Reviews 2011;15(9):4554–71.
[11] Thounthong P, Chunkag V, Sethakul P, Davat B, Hinaje M. Comparative study of fuel-cell vehicle hybridization with battery or supercapacitor storage device. IEEE Transactions on Vehicular Technology 2009;58(8):3892–904.
[12] Burke AF. Batteries and ultracapacitors for electric, hybrid and fuel cell vehicles. Proceeding of IEEE 2007;95(4):806–20.
[13] Wikipedia. Electric double-layer capacitor. From website: 〈http://en.wikipedia.org/wiki/Electric_double-layer_capacitor〉; 2012.
[14] Burke A. Ultracapacitors: why, how, and where is the technology. Journal of Power Sources 2000;91:37–50.
[15] Farcas C, Petreus D, Ciocan I, Palaghita N. Modeling and simulation of supercapacitors. Design and technology of electronics packages, (SIITME) Gyula, Hungary; 2009.
[16] Markvart T. Solar electricity. West Sussex: John Wiley & Sons; 2001.
[17] Barrie JWB, Mecrow C, Jack AG, Atkinson DJ, Freeman AJ. Drive topologies for solar-powered aircraft. IEEE Transactions on Industrial Electronics 2010;57 (1):457–64.
[18] Wikipedia. Silicon. Available from website: 〈http://en.wikipedia.org/wiki/Polycrystalline_silicon_photovoltaics#Forms_of_silicon〉; 2012.
[19] Garcia P, Fernandez LM, Garcia CA, Jurado F. Energy management system of fuel-cell-battery hybrid tramway. IEEE Transactions on Industrial Electronics 2010;57:4013–23.
[20] Barret S. Japanese fuel cell rail vehicle in running tests. Fuel Cell Bulletin 2006;12:2–3.
[21] Miller AR, Peters J, Smith BE, Velev OA. Analysis of fuel cell hybrid locomotives. Journal of Power Sources 2006;157:855–61.
[22] Burnett MB, Borle LJ. A power system combining batteries and supercapacitors in a solar/hydrogen hybrid electric vehicle. In: proceedings of the IEEE vehicle power and propulsion conference; 2005. p. 709–16.
[23] Camara MB, Gualous H, Gustin F, Berthon A, Bakyo B. DC/DC converter design for supercapacitor and battery power management in hybrid vehicle applications-polynomial control strategy. IEEE Industrial Electronics Society 2010;57:587–97.
[24] Azib T, Bethoux O, Remy G, Marchand C, Berthelot E. An innovative control strategy of a single converter for hybrid fuel cell/supercapacitor power source. IEEE Transactions on Industrial Electronics 2010;57:4024–31.
[25] Mierlo JV, P.Vd Bossche, Maggeto G. Models of energy sources for EV and HEV: fuel cells, batteries, ultracapacitors, flywheels and engine-generators. Journal of Power Sources 2004;128:76–89.
[26] Thounthong P, Rael S, Davat B. Control strategy of fuel cell/supercapacitors hybrid power sources for electric vehicle. Journal of Power Sources 2006;158 (1):806–14.
[27] Lovatt HC, Ramsden VS, Mecrow BC. Design of an in-wheel motor for a solar-powered electric vehicle. IEEE Electronics Power Application 1998;145 (5):402–8.
[28] Wikipedia. Solar Cell. Available from website: 〈http://en.wikipedia.org/wiki/Solar_cell〉; 2012.
[29] Castaner L, Silvestre S. Modelling photovoltaic systems using PSpice. New Jersey: John Wiley & Sons, INC.; 2003.

[30] Khatib T, Mohamed A. High efficient standalone photovoltaic power system. Saarbruecken: Lambert Academic Publishing; 2010.
[31] Subiyanto Mohamed A, Hannan MA. Photovoltaic maximum power point tracking controller using a new high performance boost converter. International Review of Electrical Engineering 2010;5:2535–45.
[32] Mallouh MA, Denman B, Surgenorb B, Peppley BA. Study of fuel cell hybrid auto rickshaws using realistic urban drive cycles. Jordan Journal of Mechanical and Industrial Engineering 2010;4(1):225–9.
[33] Arai J, Iba K, Funabashi T, Nakanishi Y, Koyanagi K, Yokoyama R. Power electronics and its application to renewable energy in Japan. IEEE Circuits and Systems Magazines 2008;8(30):69–76.
[34] Hannan MA, Ghani ZA, Mohamed A. An enhanced inverter controller for PV applications using dSPACE platform. International Journal of Photoenergy 2010;2010:1–10.
[35] Thounthong P, Davat B, Rael S. Drive friendly. IEEE Power and Energy Magazine 2008;6(1):69–76.
[36] Song Z, Guangqiang W, Songlin Z. Study on the energy management strategy of DCT-based series-parallel PHEV. International conference on computing, control and industrial engineering 2010(1): p. 25–9.
[37] Salisa AR, Zhang N, Zhu J. Modeling and simulation of an energy management system for plug-in hybrid electric vehicles. Power engineering conference, AUPEC; 2008. p. 1–6.
[38] Bedir A, Alouani ATA. Simple power based control strategy for hybrid electric vehicles.Vehicle power and propulsion conference, VPPC; 2009. p. 803–07.
[39] Karunarathne L, Economou JT, Knowles K. Adaptive neuro fuzzy inference system-based intelligent power management strategies for fuel cell/battery driven unmanned electric aerial vehicle. Journal of Aerospace Engineering 2009;224:77–88.
[40] Bahar DM, Cimen MA, Tuncay RN. Developement of control strategy based on fuzzy logic control for a parallel hybrid vehicle. In: Proceedings of the IEEE electrical and electronics engineering conference; 2010. p. 342–46.
[41] Ustun O, Yilmaz M, Gockce C, Karakaya U, Tuncay RN. Energy management method for solar race car design and application. In: Proceedings of the IEEE international on electric machines and drives conference IEMDC; 2009. p. 804–11.
[42] Wisniewski DT. Solar flair: An open-road challenge. IEEE Potentials; 2010 January/February. p. 6–9.
[43] Ibrahim H, Ilinca A, Perron J. Energy storage systems—characteristics and comparisons. Renewable and Sustainable Energy Reviews 2008;12(5):1221–50.
[44] Salameh ZM, Casacca MA, Lynch WAA. Mathematical model for lead–acid batteries. Transactions on Energy Conversion 1992;7:93–8.
[45] Sperandio GS, Junior CLN, Adabo GJ. Modeling and simulation of nickel–cadmium batteries during discharge. Aerospace Conference; 2011. p. 1–9.
[46] Green A. The characteristics of the nickel–cadmium battery for energy storage. Journal of Power Engineering 1999;13(3):117–21.
[47] Paatero J. A mathematical model for flooded nickel cadmium battery. Department of Physics, Helsinki University of Technology. 1997.
[48] Lithium-ion polymer. Wikipedia. Website from: 〈http://en.wikipedia.org/wiki/Lithium-ion_polymer_battery〉; 2011.
[49] Wehrey MC. Whats new with electric hybrid vehicle. IEEE Power and Energy Magazine 2004;2:34–9.
[50] Chen M, Rincon-Mora GA. Accurate electrical battery model capable of predicting runtime and I–V performance. IEEE Transactions on Energy Conversion 2006;21:504–11.
[51] Swan DH, Dickinson B, Arikara M, Tomazic GS. Demonstration of a zinc bromine battery in an electric vehicle. IEEE Aerospace and Electronic Systems Magazine 1994;9:20–3.
[52] Manla E, Nasiri A, Rentel CH, Hughes M. Modeling of zinc bromide energy storage for vehicular applications. IEEE Transactions on Industrial Electronics 2010;57:624–32.
[53] Choe SY, Ahn JW, Lee JG, Baek SH. Dynamic simulator for a PEM fuel cell system with a PWM DC/DC converter. IEEE Transactions on Energy Conversion 2008;23:669–80.
[54] Ceraolo M, Miulli C, Pozio A. Modeling static and dynamic behavior of proton exchange membrane fuel cell on the basis of electrochemical description. Journal of Power Sources 2003;113:131–44.
[55] Uzunoglu M, Alam MS. Dynamic modeling, design and simulation of a PEM fuel cell/ultra-capacitor hybrid system for vehicular applications. Energy Conversion and Management 2007;48(5):1544–53.
[56] Al-Baghdadi MAR. Modelling of proton exchange membrane fuel cell performance based on semi-empirical equations. Journal of Renewable Energy 2005;30:1587–99.
[57] Gao F, Blunier B, Simoes MG, Miraoui A. PEM fuel cell stack modeling for real-time emulation in hardware-in-the-loop applications. IEEE Transactions on Energy Conversion 2011;26:184–94.
[58] Correa JM, Farret FA, Canha LN, Simoes MG. An electrochemical-based fuel-cell model suitable for electrical engineering automation approach. IEEE Transactions on Industrial Electronics 2004;51:1103–12.
[59] Chiu LY, Diong B, Gemmen RS. An improved small-signal model of the dynamic behavior of PEM fuel cells. IEEE Transactions on Industry Applications 2004;40:970–7.
[60] Pasricha S, Keppler M, Shaw SR, Nehrir MH. Comparison and identification of static electrical terminal fuel cell models. IEEE Transactions on Energy Conversion 2007;22:746–55.
[61] Pasricha S, Shaw SR. A dynamic PEM fuel cell model. IEEE Transactions on Energy Conversion 2010;21:484–90.
[62] Kim J, Lee SM, Srinivasan S. Modeling of proton exchange membrane fuel cell performance with an empirical equation. Journal of Electrochemical Society 1995;142:2670–4.
[63] Sousa R, Gonzalez ER. Mathematical modelling of polymer electrolyte fuel cell. Journal of Power Sources 2005;147:32–45.
[64] Amphlett JC, Mann RF, Peppley BA, Roberge PR, Rodrigues A. A model predicting trasient response of proton exchange membrane fuel cells. Journal of Power Sources 1999;61:183–8.
[65] Amphlett JC, Baumert RM, Mann RF, Peppley BA, Roberge PR, Harris TJ. Performance modeling of the Ballard Mark IV solid polymer electrolyte fuel cell. II: Empirical model development. Journal of Electrochemistry Society, 142; 1–8.
[66] Ribeiro HA, Sommeling PM, Kroon JM, Mendes A, Costa CAV. Dye-sensitized solar cells: novel concepts, materials, and state-of-the-art performances. International Journal of Green Energy 2009;6:245–56.
[67] Kaygusuz K. Environmental impacts of the solar energy systems. Energy Source Part A 2009;31:1376–86.
[68] Khatib T, Mohamed A, Sopian K, Mahmoud M. Modeling of daily solar energy on a horizontal surface for five main sites in Malaysia. International Journal of Green Energy 2011;8:795–819.
[69] Khatib T, Mohamed A, Sopian K, Mahmoud M. Estimating ambient temperature for Malaysia using generalized regression neural network. International Journal of Green Energy 2012;9:195–201.
[70] Hannan MA, Azidin FA, Mohamed A. Multi-sources model and control algorithm of an energy management system for light electric vehicles. Energy Conversion and Management 2012;53(1):123–30.
[71] Ortuzar M, Moreno J, Dixon J. Ultracapacitor-based auxiliary energy system for an electric vehicle: implementation and evaluation. IEEE Transactions on Industrial Electronics 2007;54(4):2147–55.
[72] Miller JR. Introduction to electrochemical capacitor technology. IEEE Electrical Insulation Magazine 2010;26:40–7.
[73] Rotenberg D, Vahidi A, Kolmanovsky I. Ultracapacitor assisted powertrains: modeling, control, sizing, and the impact on fuel economy. IEEE Transactions on Control Systems Technology 2011;19:576–89.
[74] Hannan MA, Mohamed A. PSCAD/EMTDC simulation of unified series-shunt compensator for power quality improvement. IEEE Transactions on Power Delivery 2005;20(2):1650–6.
[75] Zubieta L, Bonert R. Characterization of double-layer capacitors for power electronics applications. IEEE Transactions on Industrial Applications 2000;36:199–205.
[76] Yang Z, Jianan S, Yicheng Z, Haiquan L. A new equivalent circuit model of hybrid supercapacitor with aqueous electrolyte, power and energy engineering conference; 2011. p. 1–4.
[77] Linzen D, Buller S, Karden E, Doncker RW. Analysis and evaluation of charge-balancing circuits on performance, reliability, and lifetime of supercapacitor systems. IEEE Transactions on Industry Application 2005;41: 1135–45.
[78] Lee BH, Shin DH, Song HS, Heo H, Kim HJ. Development of an advanced hybrid energy storage system for hybrid electric vehicles. Journal of Power Electronics 2009;9(1):51–60.
[79] Jarushi A, Schofield N. Modelling and analysis of energy source combinations for electric vehicles. World Electric Vehicle Journal 2009;3:1–7.
[80] Kirubakaran A, Jain S, Nema RK. A review on fuel cell technologies and power electronic interface. Renewable and Sustainable Energy Reviews 2009;13 (9):2430–40.
[81] Chakraborty A. Advancements in power electronics and drives in interface with growing renewable energy resources. Renewable and Sustainable Energy Reviews 2011;15(4):1816–27.
[82] Goekdere LU, Benlyazid K, Dougal RA, Santi E, Brice CW. A virtual prototype for a hybrid electric vehicle. Journal of Mechatronics 2002;12:575–93.
[83] Lu S, Corzine KA, Ferdowsi MA. Unique ultracapacitor direct integration scheme in multilevel motor drives for large vehicle propulsion. IEEE Transactions on Vehicular Technology 2007;56:1506–15.
[84] Lu S, Corzine KA, Ferdowsi M. A new battery/ultracapacitor energy storage system design and its motor drive integration for hybrid electric vehicles. IEEE Transactions on Vehicular Technology 2007;56:1516–23.
[85] Zenith F, Skogestad S. Control of fuel cell power output. Journal of Process Control 2007;17(4):333–47.
[86] Zenith F, Seland F, Konstein OE, Borresen B, Tunold R, Skogestad S. Control-oriented modelling and experimental study of the transient response of a high-temperature polymer fuel cell. Journal of Power Sources 2006;162:215–27.
[87] Onar OC, Uzunoglu M, Alam MS. Dynamic modeling, design and simulation of a wind/fuel cell/ultra-capacitor-based hybrid power generation system. Journal of Power Sources 2006;161(1):707–22.
[88] Bradley TH, Frank AA. Design, demonstrations and sustainability impact assessments for plug-in hybrid electric vehicles. Renewable and Sustainable Energy Reviews 2009;13(1):115–28.
[89] Baumann J. An analytical optimization method for improved fuel cell-battery-ultracapacitor powertrain. IEEE Transactions on Vehicular Technology 2009;58(7):3186–97.
[90] Bauman J, Kazerani M. A comparative study of fuel cell-battery, fuel cell-ultracapacitor, and fuel cell-battery-ultracapacitor vehicles. IEEE Transaction on Vehicular Technology 2008;57:760–9.
[91] Mekhilef S, Saidur R, Safari A. Comparative study of different fuel cell technologies. Renewable and Sustainable Energy Reviews 2012;16(1):981–9.

[92] Chao DC-H, Duijsen PJv, Hwang JJ, Liao C-H. Modelling of a Taiwan fuel cell powered scooter. In: Proceedings of the international conference on power electronics and drive system; 2009. p. 913–19.
[93] Hwang JJ. Sustainable transport strategy for promoting zero-emission electric scooters in Taiwan. Renewable and Sustainable Energy Reviews 2010;14(5):1390–9.
[94] Lukic SM, Cao J, Bansal RC, Rodriguez F, Emadi A. Energy storage systems for automotive applications. IEEE Transactions on Industrial Electronics 2008;55 (6):2258–67.
[95] Lukic SM, Mulhall P, Emadi A. Energy autonomous solar/battery auto rickshaw. Journal of Asian Electric Vehicles 2008;6(2):1135–43.
[96] Chan CC, Bouscayrol A, Chen K. Electric, hybrid, and fuel-cell vehicles: architectures and modeling. IEEE Transactions on Vehicular Technology 2010;59:589–97.
[97] Mullhall P, Lukic SM, Wirasingha SG, Lee YJ, Emadi A. Solar-assisted electric auto rickshaw three-wheeler. IEEE Transactions on Vehicular Technology 2010;59:2298–307.
[98] Mulhall P, Emadi A. Comprehensive simulations and comparative analysis of the electric propulsion motor for a solar/battery electric auto rickshaw three-wheeler. In: proceedings of the thirty-fifth annual conference of IEEE on industrial electronics; 2009. p. 3785–90.
[99] Mahlia TMI, Tohno S, Tezuka T. History and current status of the motor vehicle energy labeling and its implementation possibilities in Malaysia. Renewable and Sustainable Energy Reviews 2012;16(4):1828–44.
[100] Salisa AR, Zhang N, Zhu JGA. Comparative analysis of fuel economy and emissions between a conventional HEV and the UTS PHEV. IEEE Transactions on Vehicular Technology 2011;60:44–54.
[101] Ghorbani R, Bibeau E, Zanetel P, Karlis A. Modelling and simulation of a series parallel hybrid electric vehicle using REVS. In: Proceedings of the IEEE vehicle power and propulsion conference; 2008. p. 1–6.
[102] Blackwelder MJ, Dougal RA. Power coordination in a fuel cell-battery hybrid power source using commercial power controller circuits. Journal of Power Sources 2004;134:139–47.
[103] Hannan MA, Azidin FA, Mohamed A. Light vehicle energy management system using multi-power sources. Przeglad Elektrotechiczny (Electrical Review) 2012;3:197–204.
[104] Yang YP, Liu JJ, Hu TH. An energy management system for a directly electric scooter. Journal of Energy Conversion and Management 2011;52:621–9.
[105] Faiz J, Moayed-Zadeh K. Design of switched reluctance machine for starter/ generator of hybrid electric vehicle. Journal of Power System Research 2005;75:153–60.
[106] I. MathWorks. SimPowerSystems. MATLAB; 2008.
[107] Williamson SS, Emadi A, Rajashekara K. Comprehensive efficiency modeling of electric. Traction motor drives for hybrid electric. Vehicle propulsion applications. IEEE Transactions onVehicular Technology 2007;56:1561–72.
[108] Williamson SS, Lukic SM, Emadi A. Comprehensive drive train efficiency analysis of hybrid electric and fuel cell vehicles based on motor-controller efficiency modeling. IEEE Transactions on Power Electronics 2006;21: 730–40.
[109] Atabani AE, Badruddin IA, Mekhilef S, Silitonga AS. A review on global fuel economy standards, labels and technologies in the transportation sector. Renewable and Sustainable Energy Reviews 2011;15(9):4586–610.
[110] Ong HC, Mahlia TMI, Masjuki HH. A review on energy pattern and policy for transportation sector in Malaysia. Renewable and Sustainable Energy Reviews 2012;16(1):532–42.
[111] Bossel U. The hydrogen 'illusion' why electrons are a better energy carrier. Cogeneration and On-Site Power Production Magazine; March–April 2004. p. 55–9.
[112] Emadi A, Lee YJ, Rajashekara K. Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles. IEEE Transactions on Industrial Electronics 2008;55:2237–45.
[113] Emadi A. Handbook of automotive power electronics and motor drives. Florida: Taylor & Francis Group, CRC Press; 2005.
[114] Wang X, Shang J, Luo Z, Tang L, Zhang X, Li J. Reviews of power systems and environmental energy conversion for unmanned underwater vehicles. Renewable and Sustainable Energy Reviews 2012;16(4):1958–70.